

Program with Abstracts: Orillia '05

25th Canadian Tectonics Group Workshop

25 Years



October 28 to 30, 2005
Orillia, Ontario, Canada

Schedule of Events: 25th CTG Workshop (Orillia' 05)

Friday, October 28, 2005

- 7:30 p.m. **Meet and Greet in the Carmichael Suite, Highwayman Inn.**
- 8:15 p.m. **Briefing about the CTG field trip (Vince Vertolli, Fried Schwerdtner)**

Saturday, October 29, 2005

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- 7:00 a.m. **Breakfast-Buffer in Leacock Centre & South**
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- 8:15 a.m. **Brief remarks to open the Oral Session: Leacock North**
- 8:30 a.m. **Willem Langenberg* and Dinu Pana**
The ups and downs of Turtle Mountain, Alberta
- 8:45 a.m. **Kathryn Bethune**
Structural and tectonic setting in the south-central Rottenstone domain, Trans-Hudson Orogen, Saskatchewan
- 9:00 a.m. **Yvon Lemieux**
Significance of the Columbia River fault zone, southeastern Canadian Cordillera: insights from stratigraphic and thermobarometric constraints
- 9:15 a.m. **Lori Kennedy**
The Pootlass Shear Zone near Bella Coola, B.C. and its relationship to regional structure
- 9:30 a.m. **Andy Parmenter* and Paul Williams**
Kinematics of episodic deformation along the Canberry Valley high-strain zone in the Thor-Odin dome, Monashee Complex
- 9:45 a.m. **Philip Simony* and Sharon Carr**
Ductile thrusting vs. channel flow in the southeastern Canadian Cordillera: a 3-D model for nascent channel flow in the infrastructure of a coherent crystalline thrust sheet
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- 10:00 a.m. **Coffee/Tea, discussion, poster viewing: Leacock North & vicinity**
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- 10:30 a.m. **Rebecca Jamieson*, Chris Beaumont, C.J. Warren, M.H. Nguyen**
Thermal-tectonic evolution of the western Central Gneiss Belt: insights from numerical models of ductile flow in large hot orogens

- 10:45 a.m. Tom Krogh**
Temporal relations in the Twelve Mile Bay deformation zone
- 11:00 a.m. Dawn Kellett* and Laurent Godin**
Structural and chemical characteristics of muscovite in the Tethyan sedimentary sequence, Hidden Valley, central Nepal Himalaya: Implications for ⁴⁰Ar/³⁹Ar dating
- 11:15 a.m. Kyle Larson* and Laurent Godin**
Strain partitioning in the Main Central Thrust and the exhumed, middle crustal Greater Himalayan sequence exposed in the Kali Gandaki River valley, central Nepal
- 11:30 a.m. Joseph White* and David Copeland**
Channel flow in the Paleoproterozoic – can we see beneath Tibet?
- 11:45 a.m. Richard Bailey**
Secular evolution of thermal constraints on tectonic style
- 12:00 Noon Poster Session I (see program below): Leacock North & vicinity**
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- 12:30 p.m. Lunch: Leacock Centre and South**
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- 2:00 p.m. Manuel Duguet* and Shoufa Lin**
Structural geology of the Bird River greenstone belt, Manitoba
- 2:15 p.m. Michael Schweinberger*, Frank Fueten and Pierre-Yves Robin**
Effects of a temperature drop during simple shearing in an analogue of polycrystalline quartz
- 2:30 p.m. Dazhi Jiang**
Fabrics in crustal-scale high-strain zones: time to incorporate strain localization and tectonic transposition into numerical models
- 2:45 p.m. Yvette Kuiper*, Dazhi Jiang and Shoufa Lin**
Sheath folds in monoclinic and triclinic shear zones
- 3:00 p.m. Pierre-Yves Robin**
Internal vorticity and shear-sense indicators in tectonites
- 3:15 p.m. Christoph Schrank*, F. Füsseis, and Mark Handy**
Scaling of shear zones: a new local approach
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- 3:30 p.m. Coffee/Tea/Decaf: Leacock North and vicinity**
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- 4:00 p.m.** **Frank Fueten*, R. Stesky, P. MacKinnon, E. Hauber, K. Gwinner, F. Scholten, T. Zegers, G. Neukum, and HRSC Co-Invest. Team**
A structural study of an interior layered deposit in southwestern Candor Chasma, Valles Marineris, Mars, using high-resolution stereo Camera data from Mars Express
- 4:15 p.m.** **Paul Williams**
Why transposition by folding is incompatible with coeval thrusting
- 4:30 p.m.** **V. Ispolatov, Bruno Lafrance*, B. Dubé, M. Hamilton, R. Creaser**
Geology, structure, and gold mineralization along the Kirkland Lake Break and Larder Lake – Cadillac Deformation Zone, Abitibi Subprovince
- 4:45 p.m.** **Rogério Monteiro*, G. McDowell, J. Koronovich, A. Mackie, S. Jeffrey, and C. Hartle**
A new method of acquiring structural data from boreholes: Applications in the mineral industry
- 5:00 p.m.** **Alfredo Camacho*, B.J. Hensen, and R. Armstrong**
Waking up in the dreamtime without a thermal blanket: model for intraplate orogenesis fails the isotropic test
- 5:15 p.m.** **Pierre-Yves Robin* and Catherine Robin**
Stress distribution within descending lithospheric slabs and the consequence of the water cycle
- 5:30 p.m.** **Poster Session II: Leacock North and vicinity**
- A. F. Baird and S.D. McKinnon**
Linking stress field deflection to basement structures in southern Ontario: results from numerical modeling
- Simon D. Craggs and John G. Spray**
Transcurrent faulting in the Squaw Cap tectonic block of the Restigouche syncline, Campbellton region, northern New Brunswick
- Daniel Doman and Ulrich Riller**
Heterogeneous fabric development in the northeastern Sudbury Igneous Complex and its host rocks
- Herbert Fournier, J.K.W. Lee and Alfredo Camacho**
⁴⁰Argon/³⁹Argon geochronology of shear zones from Strangways metamorphic Complex and Oonagalabi Tongue, Arunta Inlier, central Australia
- Félix Gervais and Richard L. Brown**

Field evidence for magma mingling at the deepest structural level of the Frenchman Cap dome, southeastern Canadian Cordillera

Laurent Godin, Thomas P. Gleeson, Michael Searle, Tom D. Ullrich and Randall R. Parrish

Locking of southward extrusion in favour of rapid crustal-scale buckling of the Greater Himalayan sequence, Nar valley, central Nepal

Yvette Kuiper, Shoufa Lin, C. O. Böhm, and M.T. Corkery

Shear zones at the Superior Boundary Zone northeast of Thomson, Manitoba

Jennifer L. Marsh and Frank Fueten

Microstructures and deformation mechanisms in Lorrain Quartzite near Whitefish Falls, Ontario, Canada

Frances Mitchell, Laurent Godin, and Gema Olivo

Brittle deformation of Grenvillian structures in southeastern Ontario

Christoph Schrank, F. Fousseis, and Mark R. Handy

Scaling of shear zones: A new local approach

Michael Schweinberger, Frank Fueten and Pierre-Yves Robin

Effects of a temperature drop during simple shearing in an analogue of polycrystalline quartz

Guido Serafini and Pierre-Yves Robin

The Kaladar ‘metaconglomerate’: igneous or sedimentary protolith?

Robert M. Stesky

How to do structural geology on Mars with Orion software

Greg M. Stott and Nicole Rayner

Discrimination of Archean domains in the “Sachigo Subprovince”, northwestern Ontario

Vincent Vertolli

Precambrian geology of the Muskoka Lakes region, Central Gneiss Belt, southwestern Grenville Province

6:00 p.m. Cash Bar: Simcoe Room

7:00 p.m. Buffet Dinner: Simcoe Room

8:30 p.m. Annual GAC/SGTD meeting: Simcoe Room

Sunday, October 30, 2005

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- 7:00 a.m. Breakfast Buffet: Leacock Centre & South**
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- 8:00 a.m. Pick up box lunches for the CTG field trip**
- 8:30 a.m. Departure for CTG field trip: participants gather in front of
main entrance to the Highwayman Inn.**
- 4:00 p.m. Field trip ends in Severn Bridge**

Abstracts: 25th CTG Workshop (Orillia' 05)

Secular evolution of thermal constraints on tectonic style

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Mechanical decoupling of upper crust from deeper lithosphere allows tectonic styles which are not otherwise possible. Such decoupling requires high thermal inputs, whether from the mantle or intra-crustal radiogenic heating. By extrapolating modern heat flow data back in time, modern crustal viscosity values can be used to predict decoupling during the Archean and Proterozoic eras, at least in crust petrologically similar to a calibrated modern region (here "NG" or northwest German crust). This assumes that secular changes in ductility are predominantly associated with changes in thermal activation. Such predictions suggest that NG-type crust, given cratonic thermal inputs (defined as heat productivity and basal heat input) may have been pervasively decoupled during the early Archean, but probably became coupled before the end of the Archean. NG-type crust with thermal inputs characteristic of the Appalachians, or of cratonic crust which had not lost significant upper crustal heat productivity by erosion, would probably have remained decoupled through much or all of the Proterozoic. This limited sample suggests that during the early Archean, even crust with cratonic (low) thermal inputs may have been hot enough to have its elevation limited to below sea level by continuous extensional free-boundary gravitational collapse. A corollary conclusion is that the depths of Archean oceans were probably similar to today's. Once above sea level, decoupled continental crust would have switched to extrusion collapse as exhibited locally today by the Tibetan Plateau via the Himalayas. For thermally non-cratonic continental crust (that is, heat production higher than implied for cratonic crust), such extrusion collapse could have been endogenous throughout much or all of the Proterozoic, that is, generating mobile belts at continental boundaries which were not plate boundaries.

Linking stress field deflection to basement structures in southern Ontario: results from numerical modelling

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Analysis of stress measurement data from the near-surface to crustal depths in southern Ontario show a misalignment between the direction of tectonic loading and the orientation of the major horizontal principal stress. The compressive stress field instead appears to be oriented sub-parallel to the major terrane boundaries such as the Grenville Front, the Central Metasedimentary Belt boundary zone and the Elzevir Frontenac boundary zone. This suggests that the stress field has been modified by these deep crustal scale deformation zones. In order to test this hypothesis, a geomechanical model was constructed using the three-dimensional discontinuum stress analysis code 3DEC. The model consists of a 45 km thick crust of southern Ontario in which the major crustal scale deformation zones are represented as discrete faults. Lateral velocity boundary conditions were applied to the sides of the model in the direction of tectonic loading in order to generate the horizontal compressive stress field. Modelling results show that for low strength (low friction angle and cohesion), fault slip causes the stress field to rotate toward the strike of the faults, consistent with the observed direction of misalignment with the tectonic loading direction. Observed distortions to the regional stress field may be explained by this relatively simple mechanism of slip on deep first-order structures in response to the neotectonic driving forces.

Structural and tectonic setting of an Archean structural culmination in the south-central Rottenstone domain, Trans-Hudson orogen, Saskatchewan

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Rottenstone domain, composed of high-grade supracrustal and metaplutonic rocks, is a northeast-elongate domain situated between the Hearne craton and La Ronge domain in the Trans-Hudson orogen of Saskatchewan. The association of migmatitic metasedimentary rocks and TTG-type plutonic rocks suspected to be Paleoproterozoic in age fuelled early interpretations that this domain is the root of the La Ronge arc. Recent studies, however, indicate that Archean crust played a more substantial role in its creation. This talk presents the preliminary results of a structural study of a unique occurrence of Archean rock in the south-central part of the domain. The rock in question, a strongly deformed granodioritic “augen” gneiss dated as ≥ 2500 Ma, is exposed in the core of a doubly-plunging antiform centred on Black Bear Island Lake. Although superficially appearing to occupy the structurally lowest level of a simple dome, structural analysis indicates a complex history of polyphase folding between the augen gneiss and interdigitated metasedimentary migmatite. The latest generation of northeast-trending, doubly-plunging, upright to locally overturned folds (F_{n+2}) is superposed on an earlier set of tight to isoclinal recumbent folds (F_{n+1}) with northwest-trending axes, producing interference patterns transitional between Type 2 and 3. An even earlier phase (F_n) of tight folding is implied by the presence of rootless isoclinal folds in F_{n+1} fold limbs. The F_{n+1} recumbent folds are tentatively correlated with northwest-trending, southwest-verging F_3 folds and thrusts in the Reindeer zone to the southeast. These relationships, along with the fact that the augen gneiss has a geochemical and isotopic affinity closer to the Hearne than to the Sask craton, suggests that southwestern Rottenstone domain was developed through intense thrust-fold imbrication of Hearne basement and an overlying package of synorogenic (Paleoproterozoic) psammopelitic rocks under high-grade metamorphic conditions. Further work is planned to test and more fully elucidate this general model.

Waking up in the dreamtime without a thermal blanket: model for intraplate orogenesis fails the isotopic test

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The factors that control intraplate orogenesis are controversial because of the difficulty in explaining how cold thick crust can deform in areas where there is no obvious deformation mechanism. A recently proposed model (thermal blanket model) has received considerable attention because it explains intraplate orogeny by coupling long-term self-heating through radioactive decay of basement with thermal blanketing by overlying sediments. This model has been tested in one of the type areas in central Australia: the Proterozoic Musgrave Complex reworked in an early Cambrian orogeny. We have determined the source of the pre- and post-orogenic sediments in the Amadeus Basin immediately to the north of the reworked basement, including the fan deposits associated with uplift, comprising Uluru (Ayers Rock) and Kata Tjuta (Olgas). Detrital zircon age populations indicate that all basin sediments were derived from the Musgrave Complex, which was therefore emergent, rather than covered by sediments as required by the model. In the basement the preservation of Mesoproterozoic mica ages during transpressive burial to up to 40 km at ca. 550 Ma, indicates that the associated thermal pulse was short-lived, not long, as envisaged in the model. We conclude therefore that the thermal blanketing model is inconsistent with the isotopic data and that selective reworking during a short-lived transpressive event is related to plate motions during the Pan-African Orogeny.

Transcurrent faulting in the Squaw Cap tectonic block of the Restigouche syncline, Campbellton region, northern New Brunswick

Simon D. Craggs, John G. Spray

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Regional scale faulting in the Campbellton region of northern New Brunswick is largely attributed to Acadian deformation as a result of the convergence of Avalonian and peri-Gondwanan terranes with the Laurentian margin. Previous work has suggested that all ENE-WSW trending regional faults exhibit only strike-slip tectonics. However, fieldwork undertaken this year has yielded results that indicate a relatively significant vertical component to both the Squaw Cap and Sugar Loaf faults, with the Black Lake Fault remaining largely dextral strike-slip.

High angle south directed reverse movement along the Sugar Loaf Fault is indicated by slickensides, striations and flexure-slip folding to the north of the fault. This may have been due to a reactivation of a pre-existing dextral strike-slip fault in response to the final docking of Gondwana. Movement along the Squaw Cap Fault is likely to have been predominantly dextral oblique-slip, with compression directed north to northwest. Two major, medium- to high-angle reverse faults, the Sellarsville and Sellarsville East faults, observed to the west of the field area, show evidence of southeast directed compression.

A strong asymmetry to the development of strain has been observed across the Black Lake and Sellarsville faults. South of Robinsonville, the Black Lake Fault exhibits shearing of warped and folded medium bedded, calcareous sandstone and siltstone in the southern wall of the fault. Relatively little deformation, with the exception of rare kink folding, is seen in the thin bedded siltstone to the north of the fault. At Camp Harmony, a lithological change between thick bedded sandstones of the Whites Brook Formation in the hanging wall, and thin bedded siltstones of the Pabos Formation in the footwall of the Sellarsville fault causes a disparity in deformation features across the fault. Apart from some gentle open folding, little deformation is shown in the hanging wall. Duplexing of the siltstone, along with abundant mineralisation and pseudotachylyte formation along several slip interfaces is manifest in front of the main fault plane in the footwall. North of Camp Harmony in the area locally known as the Rafting Ground, a slaty cleavage is clearly developed in Pabos Formation rocks in the hanging wall, with none developed in the footwall.

Overall burial depth is interpreted to have been relatively shallow, (<9 km), based on the limited metamorphism (low greenschist facies), vitrinite reflectance studies and the brittle nature of deformation. However, frequent sigmoidal fracturing of all lithotypes suggest a large zone of compression across the area. It is suggested in this abstract that the field area represents a large dextral transcurrent fault system, bounded by the dextral strike-slip Black Lake Fault to the South and the dextral strike-slip Sugar Loaf Fault to the North. Overall compressional tectonics are proposed to have taken place between the two bounding faults as exhibited by the Sellarsville, Sellarsville East and Squaw Cap faults. The differing styles of faulting seen within the proposed dextral transcurrent fault system could suggest multiple reactivations of the dominant fault planes. If so this will have implications for potential tectonic hydrocarbon trap development in the Squaw Cap tectonic block of the Restigouche syncline.

Heterogeneous fabric development in the north-eastern Sudbury Igneous Complex and its host rocks

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The 1.85 Ga Sudbury Igneous Complex (SIC) in central Ontario is now widely considered to be the erosional remnant of a deformed impact melt sheet, about 2.5 km in thickness. Previous workers considered non-cylindrical folding and NW-directed reverse faulting as the main structural processes that formed the funnel-shaped geometry of the SIC. Structural studies support this model in the southern part of the impact structure, where greenschist-facies metamorphic tectonites accomplished structural uplift of the southern SIC by NW-directed reverse shearing. However, little evidence for fold-induced strain has been reported from the weakly metamorphosed NE-lobe of the SIC, characterised by maximal curvature in plan view. The objective of this structural study is, therefore, to assess the highly variable structural inventory of the SIC and its host rocks in terms of post-emplacment deformation mechanisms. The study is based on published and newly acquired structural data.

Impact breccias of the Onaping Formation and post-impact metasedimentary rocks overlie the SIC, which in turn rests on Archean granite, gneiss and greenstone, as well as Paleoproterozoic metavolcanic and metasedimentary rocks. Brittle faults striking N-S are developed in all lithologies, whereby kilometre-scale faults cut the NE-lobe's eastern limb causing variable magnitudes of strike separation of its contacts. By contrast, ductile strain fabrics are pervasive only in the Onaping Formation, forming the core of the lobe, and in Archean greenstone and Paleoproterozoic marble of the Espanola Formation, forming the outer arc. The SIC and adjacent Archean granite are devoid of ductile strain fabrics. Planar ductile fabrics in the Onaping Formation strike NE-SW, whereas the strike of equivalent fabrics in greenstone changes from NE-SW to NW-SE with increasing distance from the SIC. The most prominent fabrics in the Espanola Formation are pressure-solution planes that are concordant to axial planes of folded strata. These fabrics are discordant to planar mineral fabrics in the other units but sub-concordant to the NW-SE striking lithological contacts of this formation. Thus, marble of the Espanola Formation served likely as a ductile detachment layer, accomplishing differential shear between more competent quartzite units confining the marble.

Linear shape fabrics in the Onaping Formation and Archean greenstone, as well as small-scale fold axes in the Espanola Formation, plunge uniformly towards the SE. Where ductile fabrics are developed, a general concordance of brittle faults and ductile planar shape fabrics is observed. Kinematic analysis of small-scale brittle shear faults near first-order discontinuities indicates NW-SE to E-W shortening, i.e., orthogonal to foliation surfaces at the same localities. This points to a similar deformation regime during ductile and brittle deformation. Moreover, the strike of ductile planar shape fabrics in Archean greenstone and the Onaping Formation is parallel to the symmetry axis of the NE-lobe in plan view, whereby the foliation in greenstone displays some fanning. Spatial continuity between ductile fabrics in the Onaping Formation and greenstone through the SIC and adjacent granite is maintained by brittle faults on variable scales. The observed structural characteristics can be explained in terms of a single tectonic process, i.e. large-scale, non-cylindrical folding of the SIC and its host rocks. Fabric development depends, thereby, strongly on the mechanical properties of a given rock type and on strains induced by local fold-adjustment rock flow.

Structural geology of the Bird River Greenstone Belt, Manitoba

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The Bird River greenstone belt is situated in the Superior craton between the English River subprovince to the north and the Winnipeg River subprovince to the south.

The Bird River belt is composed of various tectono-stratigraphic units. Along the north margin of the belt, the Lamprey Falls Formation, consisting of pillowed basalt with intercalated tuff and iron formation represents the oldest rocks. The mafic/ultramafic Bird River Sill is situated along the south side of the Lamprey Falls Formation and is dated by U/Pb zircon at 2745 ± 3 Ma (Wang, 1993). Southward, the Peterson Creek Formation containing rhyolite flows, pyroclastic breccia, lapillistone tuff and volcanic sandstone, is a slightly younger with an age at 2740 ± 4 Ma (Wang, 1993). To the East, the Flanders Lake Formation is composed of polymictic conglomerate and metamorphosed lithic arenite. The Booster Lake Formation is composed mainly of greywacke-mudstone turbidites and overlain the previous cited formations. To the south, the Booster Lake Formation is overlain by the Bernic Lake Formation which is composed of basalt, andesite, dacite, rhyolite and a minor amount of conglomerate and sandstone.

The individual formations described above are generally bounded by east-west trending faults. None stratigraphic contact has been preserved. All stratigraphic formations have been subjected to regional metamorphism up to amphibolite facies grade, with subsequent greenschist facies retrogression (Trueman, 1980).

Until now, the kinematic history responsible of the structural pattern of the belt was unknown. During the summer of 2005, field investigations showed that the Bird River greenstone belt has experienced polyphase ductile deformation. The first D1 event consists of a south side up shearing coeval with amphibolite facies metamorphism which causes the superposition of the Bernic Lake Formation upon Booster Lake Formation overlying itself Flanders Lake and Peterson Creek formations. A second event, D2, reworks the previously structured units by dextral strike-slip movements coeval with the emplacement of pegmatitic granites. In Flanders Lake Formation, this D2 event is responsible of the NW-SE trending axis upright folds whereas Peterson Creek and Booster Lake formations are affected by dextral shearing with hectometre-scale folds and faults. A latter D3 event consists of a sinistral strike-slip tectonic.

References

- Trueman, D.L., 1980. Stratigraphy, structure and metamorphic petrology of the archean greenstone belt at Bird River, Manitoba. Ph.D. thesis, University of Manitoba, 150 p.
- Wang, X., 1993. U-Pb zircon geochronology study of the Bird River Greenstone Belt, southeastern Manitoba. MSc thesis, University of Windsor, Windsor, Ontario. 96p.
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⁴⁰Ar/³⁹Ar Geochronology of shear zones from Strangways Metamorphic Complex and Oonagalabi Tongue, Arunta Inlier, central Australia

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Shear zones play an active role in the exhumation and deformation of geological terranes, and they can serve as time markers in their geologic evolution. Two areas studied (the Strangways Metamorphic Complex and the Oonagalabi Tongue) form part of the Arunta Inlier, central Australia, a large (200000 km²) metamorphic complex preserving a geological history spanning 1600 Ma. Granulites-facies rocks that belong to the Strangways Metamorphic Complex and the Oonagalabi Tongue are now exposed at the surface. Palaeozoic amphibolite-facies metamorphism associated with several orogenic pulses reworked the granulites and resulted in high-strain zones throughout the Arunta. The Larapinta Event, the oldest of the Palaeozoic metamorphic events (480-440 Ma), is mainly evident in the eastern Arunta (Harts Range and Oonagalabi Tongue) and is associated with the development of a failed rift and pull-apart basins. The Alice Springs Orogeny (400-300 Ma) reworked the entire Arunta Inlier and was associated with significant crustal shortening resulting in the final exhumation of the Paleoproterozoic granulite-facies rocks to shallower crustal levels. This study aims to determine whether the final exhumation path of the central Arunta (Strangways Range) which has dominantly seen the Alice Springs Orogeny is significantly different from the eastern Arunta.

Biotite, muscovite and hornblende in shear zones from both terranes were analysed by ⁴⁰Ar/³⁹Ar dating. Preliminary results from the Yambah Shear Zone in the Strangways Range yield biotite and muscovite ages of 393.1 ± 0.3 (MSWD=0.8, 80.4% of the ³⁹Ar) and 343.7 ± 0.5 (MSWD=1.2, 64.2% of the ³⁹Ar) Ma (1σ) respectively. Biotite from a kyanite schist gives an age of 407.8 ± 0.3 (MSWD=0.8, 94.8% of the ³⁹Ar) Ma (1σ), and two hornblendes from calcilicates gneisses give ages of 384 ± 2 (MSWD=0.8, 92.8% of the ³⁹Ar) and 375 ± 2 (MSWD=0.7, 100% of the ³⁹Ar) Ma (1σ). Samples from the Oonagalabi Tongue come from 4 shear zones along its northern boundary with the Harts Range. Hornblende from a tonalite and a granulite respectively, yield ages of 356 ± 8 (MSWD=0.4, 100% of the ³⁹Ar) and 364 ± 1 (MSWD=0.5, 98.7% of the ³⁹Ar) Ma (1σ). Biotites from three metapelites and one calcilicate yield ages of 383.3 ± 0.4 (MSWD=1.3, 77.1% of the ³⁹Ar), 327.8 ± 0.7 (MSWD=0.7, 90.9% of the ³⁹Ar), 350.6 ± 0.4 (MSWD=0.5, 69.7% of the ³⁹Ar), and 317.2 ± 0.4 (MSWD=1.4, 73.9% of the ³⁹Ar) Ma respectively. These preliminary results show a range of ages which we tentatively ascribe to the different metamorphic events throughout the Arunta, possibly reflecting different tectonic stages at various crustal levels during the exhumation of the crust throughout the Alice Springs Orogeny.

For future work, single K-feldspars crystals will be used to obtain an independent cooling history which can be directly compared with the cooling histories derived from various minerals with different closure temperatures.

A structural study of an interior layered deposit in southwestern Candor Chasma, Valles Marineris, Mars, using high resolution stereo camera data from Mars Express

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The Interior Layered Deposits (ILD) within the Valles Marineris depressions on Mars may be of sedimentary, volcanic or eolian origin. Previous studies have documented their surface texture and geomorphic features, but little is known about their internal geometry and structural setting.

Interior Layered Deposits within Western Candor Chasm of Valles Marineris, Mars, are examined using data from the High Resolution Stereo Camera of the Mars Express mission. The image and calculated digital elevation model allow layering attitudes to be measured using ORION software. Most ILD layers dip down the topographic slope, suggestive of draping over a basement topography consisting of rotated fault blocks. An unconformable relationship between two ILD units indicates at least two stages of deposition. Exposed, rotated fault blocks of basement lithology appear to penetrate the cover of ILD deposits at two locations.

Relatively simple structural information can help to resolve competing hypotheses and lead to a better understanding of the geological history of the region.

Field evidence for magma mingling at the deepest structural level of the Frenchman Cap Dome, Southeastern Canadian Cordillera

Felix Gervais and Richard L. Brown

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The Frenchman Cap dome is one of the two domal culminations of the Monashee Complex, southeastern Canadian Cordillera. This dome is mantled by migmatitic metasediments and cored by migmatitic orthogneisses. There is currently a vivid debate concerning the age of the core migmatites, and a geochronological study is underway to resolve this issue. Here, we report a rather unusual case of mingling relationships between metabasaltic dykes and migmatitic orthogneiss observed in the core of the dome.

At the deepest level, a large ultramafic (~300m wide) pod composed of hornblende gabbros, hornblende gabbro-norites and norites, is dissected by a swarm of granitic dykes that show lobate contacts with dismembered ultramafic blocks, suggesting liquid-liquid contact. Similar relationships have also been observed at the margin of mafic/ultramafic dykes surrounding the ultramafic pod. At another locality, the complete spectrum from mingling to mechanical mixing have been observed, including: metric gabbroic dykes surrounded by granitic melt; composite dykes formed by pillowed mafic enclaves floating in granitic material; and hornblende rich enclaves that mix with felsic melt to ultimately form a hornblende granitoid.

Another peculiar feature is the increase in grain size observed at the margin of most mafic dykes intruded into migmatitic orthogneiss, which suggest a fluid-related emplacement reaction. The dykes were probably affected by the regional metamorphism after their crystallization, owing to the occasional presence of cpx-bearing leucosome and coronitic garnets at their margin.

Finally, on a large cliff located ~2 km structurally above the ultramafic pod, vertical mafic dykes are interconnected by apophyses that intrude into the migmatitic layering to form sills. The fact that the vertical dykes are incompetently folded and that the fold limbs and apophyses are boudinaged constitute good evidences of syn-tectonic intrusion.

Therefore, field observations indicate that a major event of mafic magmatism took place in the core of Frenchman Cap dome. Such a magmatic event generates heat that can greatly soften the lower/middle crust. Determining if this event is related to the Cordilleran orogeny or not is thus of uttermost importance for our comprehension of the tectonic evolution of this part of the orogen.

Locking of southward extrusion in favour of rapid crustal-scale buckling of the Greater Himalayan sequence, Nar valley, central Nepal

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The South Tibetan detachment system (STDS) bounds the upper limit of the Greater Himalayan sequence (GHS), which consists of the exhumed middle crust of the Himalaya. In the Annapurna range of central Nepal, the GHS comprises a sequence of amphibolite-grade augen gneisses with a 3.5 km thick leucogranite at the higher structural levels (Manaslu granite). Two major low-angle normal sense shear zones have been mapped. The Chame detachment has similar grade metamorphic rocks above and below and is interpreted as a ductile shear zone wholly within the GHS. The Phu detachment is a ductile-brittle normal fault which wraps around the top of the Manaslu leucogranite and defines the uppermost, youngest strand of the STDS, placing folded unmetamorphosed Palaeozoic rocks of the Tethyan sedimentary sequence above the GHS. Our data indicate that ductile flow and southward extrusion of the GHS terminated with cessation of movement on the brittle upper strand of the Phu detachment at ca. 19 Ma, which was followed almost immediately by crustal-scale buckling. Argon thermochronology reveals that the bulk of the metamorphic rocks and lower portions of the Tethyan sedimentary sequence in the Nar valley cooled through the hornblende, biotite, and muscovite closure temperatures at ca. 16 Ma, suggesting very rapid cooling rates. The thermochronology results indicate that this cooling occurred 2-3 Myr earlier than in the frontal part of the extruded GHS. Although the extrusion in the frontal part of the GHS must have locked at the same time as in the Nar valley, the exhumation there was slower, and most probably only assisted by erosion, rather than by rapid folding as is the case in the Nar valley. This buckling indicates a step northward in deformation within the Himalayan belt, which may be a response to a lower deforming taper geometry in the foreland.

Geology, structure, and gold mineralization along the Kirkland Lake Break and Larder Lake – Cadillac Deformation Zone, Abitibi Subprovince

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The Larder Lake – Cadillac deformation zone (LLCDZ) is a ~200 m to 500 m wide transpression zone along the contact between the ca. 2680 Ma to 2670 Ma alkalic volcanic rocks and conglomerate of the Timiskaming assemblage and tholeiitic basalts of the 2705 Ma Larder Lake Group. Four generations of structures are observed within the LLCDZ. The LLCDZ is a D2 structure that affects both the Timiskaming and Larder Lake rocks. It postdates early D1 accretion of volcanic terranes, which are unconformably overlain by rocks of the Timiskaming assemblage. The trend and attitude of the LLCDZ is defined by a chloritic and sericitic foliation (S2) dipping steeply to the north or south. S2 contains a steeply- to moderately E-plunging stretching lineation (L2) expressed by elongate pebbles and clasts. S2 and L2 are overprinted by a north-trending differentiated crenulation cleavage (S3) and open folds (F3), which formed during orogen-parallel east-west D3 compression. D3 structures are in turn overprinted by NE-trending Z-shaped folds (F4) and associated axial plane crenulation cleavage (S4). These structures formed during D4 dextral reactivation of the deformation zone. S-shaped F5 folds, which overprint all D2 to D4 structures, are the youngest structures in the deformation zone. Gold deposits plunge parallel to L2 and native gold occurs in quartz-carbonate veinlets or bands parallel to S2, suggesting that gold was deposited during D2. The mineralized zones were subsequently modified during the younger deformation events.

The Kirkland fault belongs to a system of brittle faults that parallels the LLCDZ. The faults are narrow, generally only a few meters wide, and they have a reverse south-side-up sense of slip with a dextral horizontal component. Auriferous quartz veins are parallel to the walls of the faults. In contrast to the LLCDZ, mineralization along the Kirkland Lake fault is characterized by high Te and Mo and by the occurrence of gold as both native gold and telluride gold. The veins were either emplaced along fractures that formed during the emplacement of alkalic plutons and that were subsequently reactivated during D4 as reverse dextral faults, or they were emplaced during D4 faulting. Whether the veins were emplaced in fractures that were later reactivated during D4, or they were emplaced during D4 faulting, the Kirkland Lake fault system and LLCDZ constitute two distinct mineralization systems.

Thermal-tectonic evolution of the western Central Gneiss Belt: Insights from numerical models of ductile flow in large hot orogens

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The Himalayan-scale Grenville orogen formed on the southeastern margin of Laurentia at ca. 1200-1000 Ma. In the western Central Gneiss Belt (CGB) of Ontario, Laurentian rocks were reworked at synorogenic depths of 25-35 km during the Ottawa orogeny (ca. 1090-1030 Ma). Deformation propagated from juvenile continental arc rocks in the southeast towards older polycyclic rocks in the northwest. Widespread migmatite and granulite record peak metamorphic conditions of 750-900°C at 10-12 kb. These observations can be interpreted in the context of thermal-mechanical models for large hot orogens that incorporate a viscosity reduction over the temperature range associated with incipient partial melting. The models show a diachronous 3-phase evolution. Phase 1 is associated with crustal thickening, phase 2 with thermal relaxation, and phase 3 with lateral flow of weak middle to lower crust. A minimum 20-25 My incubation time separates phases 1 and 3. Lateral flow may be driven by a topographically-induced pressure gradient, leading to homogeneous channel flow, or by collision with a strong lower crustal indenter, leading to the creation of hot fold nappes. An intermediate flow regime may arise where disrupted lower crustal nappes become incorporated into heterogeneous channel flow.

Based on a wide range of geological, seismic, structural, petrological, and geochronological data, we propose that the high-grade rocks of the western CGB may preserve the exhumed remnants of a hot nappe-channel system active at the peak of the Ottawa orogeny. Evidence for a low-viscosity channel comes mainly from the Muskoka domain, which comprises shallow-dipping, highly migmatitic orthogneisses that extend into the thin, lobate Seguin structure. Underlying rocks of the Rosseau and Algonquin domains, in contrast, are sparsely migmatitic and contain substantial mafic to intermediate granulite. On a crustal scale, the structural style of the CGB comprises moderately dipping reflective zones suggesting a hot nappe style of deformation. Remnants of pre- and early-Ottawa nappes may be preserved in the Parry Sound and Shawanaga domains respectively; anorthosite and retrogressed eclogite bodies, common along domain boundaries, may represent fragmented remnants of lower crust incorporated into heterogeneous channel flow. Model thermal evolution produces P-T conditions compatible with data from the Parry Sound Domain and adjacent regions. These features suggest that hot nappes played a role in the tectonic evolution of the CGB and adjacent regions, and that locally they may have been disrupted by and incorporated into a low-viscosity channel developed during the Ottawa orogeny. This study shows that although melt-weakening almost certainly plays a significant role in orogenic tectonics, a range of resulting flow modes and corresponding geological features is possible - not all large hot orogens will develop homogeneous (Himalayan-style) channel flows.

Fabrics in crustal-scale high-strain zones: time to incorporate strain localization and tectonic transposition into numerical models

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Small-scale (centimeter to meters) shear zones with well defined undeformed wall rocks are simple kinematically, although the mechanics and the rheological behavior of rocks associated with the initiation and development of these zones remain less well understood. Crustal-scale high-strain zones on the other hand differ fundamentally from small-scale strain-localization zones in that the former are roughly tabular domains in the lithosphere in which the deformation is extremely heterogeneous. Although a crustal-scale high-strain zone may present simple fabrics at the stage the finite strain in the zone is high, there is ubiquitous evidence that the fabrics are products of strain localization on various scales and tectonic transposition of lithological units. The localization and transposition process is continuous in the active lifespan of the broader zone; strain localization zones and transposition layering formed earlier in the deformation may be further transposed and/or overprinted by strain localization zones. Williams and Jiang (2005, *Journal of Structural Geology* v. 27, 1486-1504) recently summarized the structural geometry in crustal-scale sub-horizontal zones. The summary appears to be applicable to most large-scale high-strain zones regardless of their orientations. The above observations clearly suggest that crustal-scale high-strain zones cannot be modeled as homogeneous domains of flow and deformation. Nor can they be regarded as simple heterogeneous domains with flow and deformation varying only in the direction normal to the zone boundary. Also, it is not practical to derive the kinematics of a crustal-scale high-strain zone through a bottom-up approach by studying the kinematics of small-scale strain localization zones as well as the process of transposition for small-scale zones are too numerous and their kinematics highly heterogeneous and non-steady.

It is time to incorporate strain localization and tectonic transposition into numerical models of crustal-scale high-strain zones. Although previous simple models reproduce the planar fabrics observed in natural high-strain zones, they are unable to explain the characteristics of many linear fabric patterns in natural zones. Some ad hoc explanations can be eliminated by natural observations. Preliminary modeling work taking into account strain localization and transposition in crustal-scale high-strain zones yields some exciting results. The modeling predicts all the characteristics of both planar and linear fabrics observed in natural crustal-scale high-strain zones.

Structural and chemical characteristics of muscovite in the Tethyan sedimentary sequence, Hidden valley, central Nepal Himalaya: Implications for $^{40}\text{Ar}/^{39}\text{Ar}$ dating.

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Throughout the central Nepal Himalaya, the Tethyan sedimentary sequence (TSS) is structurally dominated by a train of north-verging folds, in apparent contradiction to the dominantly south-propagating Himalayan orogen. The absolute age of folding is unknown, although previous structural observations have suggested the folding may predate Miocene movement of the South Tibetan detachment system. Structural mapping in Hidden valley, central Nepal, reveals three phases of deformation (D_2 , D_4 and D_5) within anchizonal to epizonal metamorphic grade Ordovician-Jurassic TSS rocks. Megascopically, D_2 is defined by large, asymmetric north-verging folds; microscopically D_2 is seen as an axial planar cleavage. Muscovite geochemistry, geochronology and microstructure is used to identify two chemically and structurally distinct generations of muscovite in the TSS, one of which is detrital (M1), and one of which is new growth (M2). Structurally, M1 is randomly oriented and intermittently rotated into S_2 and S_4 cleavage planes, while M2 forms S_2 axial planar cleavage and also occurs as growth rims on M1. Conventional $^{40}\text{Ar}/^{39}\text{Ar}$ step heating methods indicate that Proterozoic and Paleozoic detrital M1 muscovite has been weakly rejuvenated. M2 muscovite, dated by the *in situ* UV laser $^{40}\text{Ar}/^{39}\text{Ar}$ spot fusion method, is at least as young as 34.7 ± 1.7 Ma, assuming a closed system since metamorphism, which we interpret as a maximum age for F_2 folding. The UV laser shows great potential for *in situ* dating of cleavage domains. D_2 north-verging folds are Himalayan in age, likely occurring between ~ 18 -35Ma; this is the first absolute age constraint obtained for this deformation.

The Pootlass Shear Zone near Bella Coola, B.C, and its relationship to regional structure.

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The Pootlass shear zone (PSZ) is a newly discovered system of variably deformed and metamorphosed metasedimentary, volcanic, and plutonic rocks. This system was first identified by a Targeted Geoscience Initiative project for mapping the Bella Coola map sheet from 2002-2004. The Bella Coola map sheets lies within the Coast Belt, and is underlain by rocks of the Intermontane superterrane – rock of the Insular superteranne outcrop a short distance to the West. To the West of the PSZ is the Coast Shear Zone, a 1200 km, ductile shear zone that has a long, protracted history including: (1) early dextral transpressive displacements between 85 and 60 Ma; (2) northeast-side-up reverse motion between 65 and 57 Ma; and (3) normal northeast-side down motion between 57 and 48 Ma (Klepeis et al., 1999; Andronicos et al., 1999; Rusmore et al., 2001). At the latitude of Bella Coola, only the top-to-the Northwest movement has been identified. To the Southeast of the PSZS, lies the Yalakom and Tchaikazan fault systems. The Tchaikazan fault system was active as a sinistral fault in the Early Cretaceous and together with the Yalokom fault was a major player in the Eocene dextral event in the southern Coast Belt.

The reasons for this study are threefold: 1) to determine the geometry, kinematics and timing of the Pootlass shear zone system, 2) to determine its relationship with the Coast Shear zone to the West, 3) To determine its relationship with the Tchaikazan and Yalakom faults to the SE, especially in terms of a major step-over event in the late Cretaceous.

Preliminary studies of the PSZ have documented that it is at least 50 km long and 3-5 km wide, also:

1) The western part of the shear zone contains variably transposed package of meta-andesite, amphibolite and felsic dykes in faulted contact with high strained volcanoclastic and associated metasedimentary rocks. Isoclinal, shallow, to moderately plunging folds are common. S-C fabrics, shear bands and fold asymmetry consistently show a sinistral shear sense. These fabrics are overprinted by dextral fabrics, which are lower in temperature during deformation.

2) The eastern part of the shear zone contains gabbros, metabasalts and variably deformed felsic dykes. Most kinematic indicators provide a dextral shear sense (e.g. shear bands, and asymmetric boudins). Widespread flattening occurs in the east.

3) Ar-Ar from dynamically recrystallised hornblende yields a 123. ± 5.6 Ma age. A deformed dyke in metasedimentary rocks yields an age of 140.0 ± 1.0 Ma (U/Pb) and a cross cutting pluton provides an upper constraint of 67.2 ± 0.3 (Ar/Ar [biot]).

Temporal relations in the 12 Mile Bay Deformation Zone

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The publication of the tectonic models for the Muskoka – Parry Sound area by Davidson and Culshaw constituted a major advance in the understanding of this complex region. Subsequent mapping by van Berkel, Lumbers and Vertolli provided the first detailed geological maps and confirmed much of the litho – tectonic subdivisions, and geochronological studies confirm many of their conclusions. Here I will add temporal considerations to the structural and metamorphic aspects exposed along 12 Mile Bay, a high strain zone comprised of interlayered anorthosite, amphibolite, quartzite and other sediments. These are then extended to the east and south for comparison to those in the Moon River structure.

The 12 Mile Bay, E-W north dipping zone constitutes the southern limit of the N.W. lobe of the Moon River structure of Davidson, and is described by Culshaw as the re-emerging southern boundary of the south dipping Parry Sound shear zone. In this regard we note that the Parry Sound Shear Zone shows post – assembly melts dated at 1152 Ma in mafites metamorphosed at 1160 Ma at the top that are underlain by amphibolites metamorphosed at 1140Ma and deformed at 1120 Ma, that are in turn underlain by amphibolites and metasediments in which both aspects developed in the 1102 – 1110 Ma interval. Transitions appear to occur across major anorthositic layers. Footwall metadiabase zircons from five locations yield metamorphic ages between 1084 and 1089 Ma – about 20 million years after overthrust emplacement. Validity of these metamorphic zircon ages is gained by the observation that ages for multigrain zircon fractions from the garnet – pyroxene central part and the amphibolitized margin of a boudinaged metadiabase gave analytically identical concordant ages of 1084 and 1086 Ma whereas a single sharp faceted grain from a melt pod in the host gave 1085 Ma.

At the Western limit of the 12 Mile Bay section foliation parallel pegmatite that invades ruptured, rotated metadiabase dykes near the top of the zone yields near concordant zircon data that plot with 207/206 ages between 1155 and 1140 Ma whereas zircons from a post assembly pegmatite near the base from an amphibolite – felsite migmatitic highly deformed ductile zone yield a concordant age of 1100 Ma. Metadiabase zircons from the former site and three others along strike give near concordant ages between 1130 and 1150 Ma again implying some resetting, but new sharp faceted grains from a glassy metaquartzite (host to one mafite) yield consistent 1160 Ma ages. Metamorphism at 1160 Ma with minor regrowth or resetting, probably in response to the 1100Ma event or others, is implied. Followed along strike to the east the dip of the distinctive anorthosite – amphibolite assemblage is reversed in the vicinity of Moon Bay where a second fabric cuts and re-orientes the gneisses into the Healey Lake arc in the nose of the Moon River structure. Pegmatite occupying the second fabric yields an age of 1105 Ma whereas that from a metadiabase boudin neck is dated at 1100 Ma. Here clear indications of southward extension of the Moon River core is indicated. In the northeast lobe of Davidson’s Moon River structure well defined layering of (1345+/-3 Ma) tonalite and amphibolite is stitched in a ruptured zone of the later by unstrained pegmatitic infill that yields an age of 1159 Ma. Taken together results to date indicate that laminations (and probably structural emplacement) in the west and east lobes occurred at 1155 – 1160 Ma, and that the Healey Lake arc was imposed at 1105 – 1100 Ma; both episodes are coeval with the emplacement of the Parry Sound shear zone hence the Parry Sound Thrust over- rode it’s southern margin. New results however indicate reheating and ductile flow east of Healey Lake at 1040 Ma. Retrogression at this time or the introduction of lower grade units could explain the different metamorphic grade in the two structures.

Granitic units (5 sites) to the south record 1330 – 1400 Ma primary ages matching those in the Parry Sound domain and record both 1160 and 1050 Ma metamorphic growth. At one site a 1407 Ma granite has a well defined lower intercept at 1150 Ma but a late boudin infill gives a 1036 Ma age, whereas at another (40 km S.) a melt pod in an 1161 Ma host yields a 1110 Ma age. In contrast within the same structure,

metadiabase zircons at 3 sites (36,44, and 55 km S.) yield 1050 – 1060 Ma ages and boudin infill at 5 sites (36, 44, 48, 55 and 60 km S) yield ages for ductile flow at 1050 +/- 10 Ma. Thus units in the Moon River structure resemble those in the Parry Sound Domain in both primary age and time of metamorphism but differ by the presence of 1050-1060 Ma metamorphism with ductile flow as young as 1036Ma.

Extension at high (near melting) temperatures dominates in the southern part of the Moon River structure, but is also recorded at probably lower temperatures on 12 Mile Bay and the eastern extension. Here rotated – extensional ruptures in anorthosite and a dilatant infill in a tonalitic unit yield 1063 and 1052 +/- 2 Ma ages respectively.

These results indicate that multiple metamorphic episodes and reactivated deformation zones are the norm in overthrust regimes, and imply that PT paths and closure ages of titanite and other minerals are complicated by the timing and temperature of successive over/under riding tectonic components.

Shear zones of the Superior Boundary Zone northeast of Thompson, Manitoba

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The Superior Boundary Zone in northern Manitoba separates the Neoproterozoic Pikwitonei Granulite Domain or Superior Province to the southeast from the Paleoproterozoic amphibolite-grade Trans-Hudson Orogen to the northwest. Structural maps and structural and geochronological data from shear zones along the Superior Boundary Zone are presented.

Previously, movement along the Superior Boundary Zone has been interpreted in terms of a promontory model (White et al., 2002), where the Superior Province is interpreted as having moved to the northwest to collide with rocks of the Trans-Hudson Orogen. This model explains sinistral, southeast-side-up movement along the 030°-trending Setting Lake structure and Mystery Lake shear zone (along the southwest side of the promontory) and dextral, southeast-side-up movement along the 050°-trending Assean Lake shear zone (along the east side of the promontory).

Between the Setting Lake structure and the Assean Lake shear zone, the promontory model implies southeast-side-up movement along the 050°-trending Apussigamasi Lake–Burntwood River system and the northeast branch of Mystery Lake. Movement along this central part of the promontory, however, is northwest-side-up dextral. Furthermore, north-side-up dextral movement along the 110°-trending Aiken River shear zone (along the east side of the promontory) remains unexplained. A simple promontory model may therefore not explain all shear zones along the northwestern Superior craton margin. This may mean that shear zones formed at different times with, for example, movement on the Assean Lake shear zone outlasting movement on the Aiken River shear zone. Alternatively, the Superior Boundary Zone can be viewed as a zone of macroscopic brecciation, rather than a zone of rigidly moving domains. This would explain the inconsistent movement along the various shear zones and zones of brecciation found along Apussigamasi Lake and the Burntwood River.

A few timing constraints on movement along the shear zones exist. At least part of the dextral, southeast-side-up movement on the Assean Lake shear zone occurred after ~1.84 Ga, based on a U–Pb zircon age of a deformed aplite. Movement may or may not have been concurrent with <1.77 Ga sinistral and subsequent southeast-side-up movement along the Setting Lake structure (Bleeker, 1990). The Aiken River shear zone is deformed and crosscut by the Assean Lake shear zone. Therefore the Assean Lake shear zone was active until a later time than the Aiken River shear zone. However, early movement on the two shear zones, in the Paleoproterozoic or in the Neoproterozoic, could have occurred simultaneously. Various U–Pb and ⁴⁰Ar/³⁹Ar techniques are currently being utilised in order to further constrain the timing of movement on these shear zones.

Sheath folds in monoclinic and triclinic shear zones

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Using a unified mathematical model for high-strain zones, we investigate the orientation and shape of sheath folds for monoclinic and triclinic progressive deformation, in order to test whether the Hansen method is valid for various types of progressive deformation. The Hansen method is used to determine the shear direction from sheath folds. According to this method, the simple shear direction lies within the separation angle between groups of axes of folds of opposite asymmetry. Theoretically, axes of folds of opposite asymmetry are separated by a ‘separation line’. Where a separation angle exists, the separation line is commonly taken to be the bisecting line of the separation angle. We use the term ‘sheath fold direction’ for the direction of this median line. It is demonstrated that, in certain types of progressive deformation, the simple shear direction is not parallel to the sheath fold direction and, at higher strains, it does not even lie within the separation angle. The Hansen method is therefore not applicable for these types of progressive deformation.

In our model, the length along the strike of the shear zone boundary is assumed constant during deformation. The vertical pure shear strain rate along the shear zone boundary and the pure shear strain rate perpendicular to the shear zone boundary have the same magnitude with opposite signs. When the simple shear direction is parallel to one of the principal stretching directions along the shear zone boundaries, the deformation path is monoclinic. When the simple shear direction is oblique to one of the principal stretching directions along the shear zone boundaries, it is triclinic. By varying (a) the angle between the simple shear direction and the principal stretching directions along the shear zone boundaries and (b) the ratio of the simple shear strain rate to the pure shear strain rate, the rotation paths of fold axes for various types of progressive deformation can be modeled. Rotation of fold axes does not always result in the formation of sheath folds, but for the purpose of this study only cases where sheath folds do develop are considered.

Where drag folds develop into sheath folds in monoclinic transpression, the sheath fold direction indicates the simple shear direction. However, where sheath folds develop from pre-existing folds with axes initially oblique to the simple shear direction, the angle between the sheath fold direction and the simple shear direction may be very large (up to 90°).

In triclinic transpression, the sheath fold direction is oblique to the simple shear direction. Where sheath folds develop from drag folds, the angle between the sheath fold direction and the simple shear direction can be up to ~45°. At low strain values in triclinic transpression, the sheath fold direction does approximately indicate the simple shear direction, but the sheath fold is not yet fully developed (i.e. the angle between the fold axes is ~90° or more).

Sheath fold formation in transtension is complex. The ‘attractor’ to which the fold axes and any other material lines rotate is not simply the maximum principal stretching direction, as in transpression. In monoclinic transtension, it lies between the maximum principal stretching direction (perpendicular to the shear zone boundary) and the simple shear direction. In triclinic transtension, it lies somewhere in the quadrant between the maximum principal stretching direction and the simple shear direction, depending on the pure shear strain rates along the principal stretching directions and the simple shear strain rate.

The ups and downs of Turtle Mountain, Alberta

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Turtle Mountain forms part of the Livingstone Thrust sheet of the Foothills in Southwest Alberta and consists of Paleozoic carbonates and Mesozoic clastics. The dominant geological structures on Turtle Mountain are the Turtle Mountain Anticline and the Turtle Mountain Thrust. The Turtle Mountain Thrust is a splay of the Livingstone Thrust. The rocks forming the mountain are Paleozoic carbonates of the Banff, Livingstone, Mount Head, Etherington and Tobermory formations. Strata below the Turtle Mountain Thrust include clastics of the Fernie, Kootenay (which is coal bearing) and Blairmore groups.

A detailed geological map of the South Peak area allows the construction of down-plunge cross sections, displaying the various structures. For this purpose several cylindrical domains were established. The Turtle Mountain Anticline changes geometry along its trend. Near the top of South Peak it forms a type of box fold with a close to horizontal NNE trending fold axis. Towards the South the fold is tighter and the fold axis plunges between 11 and 24 degrees to the SSW. This change in geometry is described by the slightly conical nature of the anticline.

The Turtle Mountain Anticline is a modified detachment fold and can be described as a break-thrust fold. Initially, a detachment fold formed above the Livingstone Thrust. At a later stage the Turtle Mountain Thrust broke through the eastern limb of this fold. Eventually folded limestone layers with down-slope dips were situated above almost vertical sandstone, shale and coal layers. The Hillcrest Footwall Syncline below the Turtle Mountain Thrust is another remainder of the original detachment fold.

The rocks are extensively fractured. The Paleozoic carbonates are of most interest for the stability of the mountain and are only considered here. The majority of fractures are extension fractures with accompanying shear fractures related to the anticlinal fold. Measurements along 3 scan lines on the crest of Turtle Mountain (west limb of Turtle Mountain Anticline) provide a representative sample of the fracture fabric. Type I fracture sets (in the ac geometric plane) and Type II fracture sets (in the bc geometric plane) can be distinguished. In addition, there are fractures parallel to bedding and fractures making a small angle with bedding (WNW dipping set of fractures). These fracture patterns show good correspondence with fractures measured in a borehole, which was drilled for the placement of seismic sensors inside the mountain and which has a depth of 60 m. Major fissures have opened up on the crest of Turtle Mountain along the steeply ENE and SSW dipping fracture surfaces. The main ones on South Peak are called Crack #1 and #2. The opening of these fissures can be considered a neotectonic faulting process. These fissures will form the backside of a potential future rock slide from South Peak.

The down-slope dipping layers of the east limb are prone to sliding down the mountain, where the fissures provide the removal of lateral restraint for the rock, as observed in the disastrous landslide of 1903. The continuing instability of South Peak has been studied and monitored with interruptions since 1930. The installation of a state-of-the-art monitoring system on South Peak was completed in April 2005. Micro-seismic monitoring indicates the occurrence of sporadic local earth tremor events, some of which are located near the Turtle Mountain Thrust. Other deformation monitoring shows seasonal effects on the mountain.

Strain partitioning in the main central thrust and the exhumed, middle crustal Greater Himalayan sequence exposed in the Kali Gandaki river valley, central Nepal

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The Greater Himalayan Sequence (GHS) of central Nepal is interpreted to represent the exhumed, mid-crustal core of the Tertiary Himalayan-Tibetan orogen. It is bound above and below by two opposite sense shear zones, the South Tibetan detachment system (normal-sense) and the Main Central thrust (MCT; reverse-sense). These two shear zones, and the mid-crustal rocks between them, have been the focus of numerous models that have attempted to elucidate their structural and temporal relationship and the evolution of the Himalayan system. While there are differences in the extruding mechanics, all of these models require the exhumation of hot mid-crustal rocks to the surface. Early, field-based models can be grouped in two end members: 1) those that suggest the extrusion process was dominated by simple shear (Grujic, 1996), and 2) those that require significant pure shear during extrusion of the middle crust (Grasemann, 1999). Subsequent numerical models (Beaumont, 2004) have augmented field data and suggest that the rocks that comprise the GHS may represent the extruded lateral equivalents of a hot, viscous mid-crustal layer that originated within tectonically over-thickened crust. Each of these models each make testable predictions for the style of deformation, peak pressures and temperatures, and the thermal and deformational history of the mid-crustal rocks now exposed at surface.

Detailed mapping across the GHS, exposed in the Kali Gandaki valley in central Nepal, has shown that it is a highly transposed succession of pelite, calc-silicate, and granite, which have been metamorphosed to upper amphibolite facies. All of these units commonly host widespread leucogranite dykes and sills. In the MCT zone, at the base of and below the GHS, quartz lattice preferred orientation data, measured in thin sections of quartz-rich samples from a transect across the MCT zone, show that deformation is dominated by simple shear and characterized by a top-to-the-southwest sense of shear. These data corroborate preliminary results on quartz-rich tectonites, from neighbouring areas in central Nepal (Bouchez, 1981). Quartz-rich pelitic gneiss and granitic orthogneiss of the GHS show a moderately well-developed top-to-the-southwest sense of shear. However, it is difficult to analyze strain throughout the GHS because in the calc-silicate gneiss, which comprises a significant proportion of it, the strain is taken up by different minerals. The majority of measured samples suggest that the GHS was displaced to the southwest relative to underlying rocks, yet there is significant variability within the quartz petrofabric data, which may represent a complex flow-regime within an extruding mid-crustal layer.

While these preliminary data provide insight into the recent strain history within both the MCT and the GHS, more data, paired with vorticity analysis, are necessary to meaningfully address the kinematic applicability of various models for the extrusion of middle crustal rocks to the GHS of central Nepal.

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Significance of the Columbia River fault zone, southeastern Canadian Cordillera : insights from stratigraphic and thermobarometric constraints

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The present crustal architecture of the southern Canadian Cordillera is characterized by an array of normal faults, exhumed high-grade mid-crustal metamorphic complexes, and marked structural relief, the results of a period of significant regional crustal extension in the early Tertiary. The Columbia River fault zone (CRFZ), located along the Columbia River Valley in southeastern British Columbia, is one of a family of extension faults that have been interpreted to account for much of the early Cenozoic crustal extension in the southern Canadian Cordillera. On the basis of lithological, structural and metamorphic discontinuities, the CRFZ has been interpreted as a fundamental crustal-scale structure with dip-slip displacement up to 20 kilometres or more; it has also been hypothesized to mark the transition between rocks of the Shuswap metamorphic complex to the west, and lower grade rocks to the east, collectively referred to as the Selkirk allochthon. Recent detailed geological mapping and thermobarometric constraints along the southern segment of the CRFZ (Upper Arrow Lake area) are, however, difficult to reconcile with published interpretations.

Rocks west of Upper Arrow Lake (infrastructure) consist mostly of Proterozoic and Paleozoic amphibolite-facies metasedimentary rocks that preserve late Cretaceous to Paleocene peak metamorphic assemblages and early Tertiary cooling ages. To the east, the suprastructure comprises upper Paleozoic and lower Mesozoic metasedimentary rocks of the biotite and garnet zones, which were deformed in mid-Jurassic time and yield Mesozoic cooling ages. The transition from infrastructure to suprastructure is marked by a strain gradient a few kilometres thick, from weakly transposed and steeply dipping fabrics in the suprastructure, to penetratively transposed, near horizontal structures in the infrastructure. Thermobarometric estimates from metapelites in the vicinity of the CRFZ (Barrovian assemblages in the biotite through sillimanite zone) yield peak metamorphic conditions of ~550 to 680°C and ~5.5 to 7.0 kbar and suggest an attenuated metamorphic gradient. The similarity of *P-T* estimates on either side of the CRFZ suggest the metamorphic succession is apparently continuous across the fault; yet, it juxtaposes areas that were metamorphosed at different times.

We hypothesize that the CRFZ is not a major detachment structure as previously interpreted, and does not account for the exhumation of the infrastructure. Instead, we interpret the CRFZ as a zone of multiple, moderately- to steeply-dipping brittle faults with limited dip-slip displacement. Foliation-parallel zones of intense transposition and tectonic thinning produced the attenuated metamorphic sequence between suprastructure and infrastructure, and juxtaposed domains with different thermal histories.

Microstructure and deformation mechanisms in the Lorrain Quartzite near Whitefish Falls, Ontario, Canada

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The Lorrain quartzite is a member of the Huronian Supergroup of the Southern Province, Ontario. A section of the Lorrain is studied along a north/south transect across the LaCloche syncline, located in Whitefish Falls. The stratigraphic sequence across the syncline is preserved, and present on each fold limb. Rocks with the smallest grain size and lowest mica content are located close to the core of the fold, while coarser grained, mica rich rocks are situated at the northern and southern most extend of the transect.

Deformation mechanisms vary with lithology and with position across the fold. Pressure solution appears to be the dominant deformation mechanism in the more mica rich units. In finer grained, mica poor samples, grain boundaries are crenulated; grains display undulose extinction and evidence of grain boundary migration. Samples closest to the axial trace also show a high amount of trans- and inter-granular fracturing. These fractures cut migrated boundaries and hence post-date grain boundary migration.

All samples across the fold display a preferred orientation of quartz *c*-axes. The orientation of single and type II girdle fabrics is the same across the syncline. Formation of these fabrics can therefore not be the result of strain related to the folding process.

Brittle deformation of Grenvillian structures in Southeastern Ontario

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This study aims to examine the brittle deformation history in Proterozoic basement rocks, Paleozoic cover rocks and Pleistocene sediments along and adjacent to ancient shear zones in the Grenville Province. The goal of this project is to determine if Grenvillian shear zones may have experienced recent reactivation. Lineament, joint and fault patterns were measured and rock samples collected along the Central Metasedimentary Belt boundary thrust zone (CMBbtz) in the region from Coboconk to Hall's Lake, in Southeastern Ontario. Preliminary geometric analysis suggests there are 3 prominent joint sets, including a subhorizontal joint and two subvertical joints. The trend of the most pervasive subvertical joint set varies along the CMBbtz from predominantly NW-SE in the southern study area to mostly NE-SW in the north. Distribution of joint orientation across the CMBbtz from east to west suggests there is a change in deformation patterns from NE-SW and NW-SE to predominantly E-W trending joints. A comparison of brittle deformation in the CMBbtz with the younger Paleozoic cover rocks and Pleistocene sediments suggests the NW-trending joints are associated with a post-Pleistocene event, possibly related to glacial rebound or far-field neotectonic stresses. Further analysis of these trends will help to better constrain the relative ages of deformation, and their dynamic compatibility with the in-situ present-day stresses. It is anticipated that this study will lead to an increased understanding of recent deformation history and seismic hazard potential for southeast Ontario.

A new method of acquiring structural data from boreholes: Applications in the mineral industry

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The use of borehole data in constructing enveloping surfaces to ore bodies is well known to resource and mine geologists, who must determine, with increasing degree of precision and accuracy, the three-dimensional geometry of mineralized zones. The less is known about the shape of a mineralized zone or ore body, the more drilling is required to constrain their shape and grade, which considerably increases expenditures in an exploration project. Structural information from core and borehole probes can considerably reduce the time and money spent on delineating ore bodies or mineralized zones, while increasing the confidence level of geological interpretation.

The shape of an ore body or mineral-rich zone is intrinsically related to the genetic processes that formed the mineralization. Several aspects of modeling the final preferred three-dimensional shape of mineralized zones are discussed in the literature. But structural data are not fully used at present as a geometric constraint in ore deposit modeling. An increase of confidence in interpolated or extrapolated outer contacts and the internal geometry of ore bodies justifies the acquisition of structural data. In general, the use of structural data promises to enhance the reliability of mineral resources studies. We foresee that the Australasian Joint Ore Reserves Committee (JORC) and Canadian CIM Standards on Mineral Resources and Reserves, amongst others, will add to their codes the requirement of obtaining precise and accurate structural data.

Planar, linear and other structural elements found in drill core, especially their spatial orientation, provide crucial information to the structural analyst of ore deposits. Currently available methods for extracting structural data from oriented drill core (Vearncombe, and Vearncombe, 1998; Marjoribanks, 2002; Vearncombe, 2003-1) have various degrees of precision and accuracy. The use of some methods is time-consuming and/or limited to measuring only planar structures. (Linear features and kinematic indicators are disregarded or obtained in such ways that they require post-measurement projection and geometric manipulation. Borehole imaging probes are also a good source of structural data; however, only planar features can be obtained from images of the borehole wall.

Here we introduce a new method in which the orientation of planar and linear structural elements, together with the geometry of asymmetric structural features, is obtained in oriented drill core or televiewer images with high precision and accuracy. This is accomplished by using the MK-Method (Monteiro 2002 and Monteiro and Koronovich, 2002), as well as other procedures developed at Inco Exploration (McDowell et al, 2003 and Monteiro et al. 2005) We will illustrate the usefulness of the method in a few case studies. In addition, we will discuss procedures used where drill cores are not precisely oriented. In such cases, it may be necessary also to test for internal consistency of different structural scenarios. All methods and procedures presented in this talk provide a framework for ore deposit modeling and exploration. The methods have been extensively tested and used at Inco Exploration.

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Kinematics of episodic deformation along the Cranberry Valley High Strain Zone in the Thor-Odin Dome, Monashee Complex

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A set of approximately north-striking lineaments defines the position of the Cranberry Valley High Strain Zone (CVHSZ), a diffuse and anastomosing deformation zone in the Cranberry Mountain region of the Thor-Odin dome, Monashee Complex. Here, deeply incised east- and north-trending valleys allow access to a three-dimensional section through a mid-crustal shear zone. The CVHSZ is roughly coincident with a north-trending periclinal (antiformal) basement-cored structure mantled by a discontinuous sequence of marble, paragneiss, quartzite, calc-silicate, and amphibolite tentatively correlated with the Monashee 'cover' assemblage. A regionally persistent transposition foliation (S_T) is ubiquitous throughout the Monashee Complex. Therefore, although the entire complex can be designated as a 'high strain zone', the CVHSZ deserves distinction because it represents an internally consistent zone within which S_T and its related fabric elements are bound on either side by rocks that do not directly share its structural affinity. The zone is postulated to extend southward along the western flank of the Thor-Odin dome. Continuation northward is less traceable due to poor exposure. A further complexity is introduced by the development of a pervasive extensional overprint throughout the complex.

In order to highlight the uniqueness of the CVHSZ, it is first necessary to briefly outline some of the regional, complex-scale, structures. The dominant mesoscopic feature is the S_T fabric preserved in some stage of progressive top-to-the-northeast non-coaxial shear. Drag folds initiate with northwest trending axes and rotate counterclockwise towards parallelism with the southwest-plunging stretching lineation. The distribution of all linear structures defines a shallow dipping girdle interpreted to represent the shear plane. A shallow southwest-plunging point maximum indicates convergence towards the regional shear direction on this plane. Fold enveloping surfaces tend to dip steeply approximately towards the north or south. In contrast, the distribution of fold axes from within the CVHSZ generally define a steeply dipping ($>70^\circ$) north- to north-northwest-striking girdle interpreted to represent a sub-vertical shear plane. Variations in orientation of mesoscale folds within the CVHSZ are used to distinguish three types of structural domains. (1) Domains of upright asymmetric folds (z-shaped when viewed from the south) whose axes plunge sub-horizontally to shallowly north or south. (2) Domains of asymmetric folds (s- or z-asymmetry down plunge) whose axes vary regularly from horizontal to vertical and tend to converge towards a sub-vertical plunge. (3) Transitional domains where fold axes plunge in any direction between the orientation of the shallow southwest-dipping, and the steep north- to north-northwest-striking, shear planes, respectively. These transitional domains also preserve evidence of clockwise rotation of the fold axes as they converge towards the north-striking shear plane orientation. Similarly, fold enveloping surfaces rotate into an east- or west-dipping orientation within the CVHSZ.

The clockwise rotation of planar and linear structures, and a well-defined, steeply dipping shear plane suggests that, at some interval, the CVHSZ acted as a ductile, north-south-oriented dextral shear zone. Shallow to sub-horizontally plunging folds with axial planes that are sub-parallel to the north-striking shear plane, may suggest that movement was dominantly transcurrent. In addition, sub-horizontal to shallowly plunging slickenside lineations are locally preserved on steep, north-striking dislocation planes. The domainal rotation of fold axes into steeply plunging orientations suggests that at some interval a component of normal movement occurred within the CVHSZ. Shear band asymmetry and offset markers suggest overall west-side-down offset. Steeply plunging slickenside lineations preserved on some dislocation planes, further strengthen this argument. The normal movement is interpreted to represent a re-activation of an already developed steeply-dipping transcurrent fault zone.

It is unclear whether the deformation within the CVHSZ can be explained by a single protracted event or if it was characterized by a number of discrete episodic pulses. The long-lived nature of major transcurrent boundaries, e.g. the San Andreas Fault Zone, may argue for the latter. The aforementioned observations may also have very important implications for the Baja B.C. hypothesis.

Stress distribution within descending lithospheric slabs and the consequent water cycle

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A significant amount of water appears to be transported deep into Earth's upper mantle by a number of minerals that descend with the lithospheric slab. Elementary stress analysis shows that, within the transition zone, the maximum principal compressive stress trajectories are oriented such that any fluid released should generally flow into the slab. Within that slab, H₂O will be dissolved into transition zone minerals ringwoodite and wadsleyite, and thus continue downward until it reaches the bottom of the transition zone. Lower mantle minerals (perovskite, magnesiowüstite) can incorporate very little H₂O and the breakdown of H₂O-saturated ringwoodite is, in effect, a dehydration reaction. The water liberated will percolate upward along the slab until it encounters ringwoodite or wadsleyite that is not yet H₂O-saturated. If it does, H₂O is dissolved into these minerals and descends again to the bottom of the transition zone. Eventually, the whole slab becomes H₂O-saturated. When this H₂O cycle is fully primed, perhaps after 5,000 to 8,000 km of subduction, the water going down with hydrous minerals in subducted crust has to be balanced with (i) that rising through the mantle wedge and responsible for arc magmatism, (ii) that rising near the trench and pouring out through serpentine sea-mounts, (iii) that leaking in other levels of the upper mantle, and (iv) that stranded in flat lying slabs. The latter may eventually be responsible for wet-spot magmatism at significant distances from the subduction zone.

An H₂O-fluid percolating through the lithospheric slab readily accounts for deep-focus earthquakes and for some features of intermediate focus earthquakes. It should also have a significant impact on location and geochemistry of fluids and melts generated in the upper mantle. In particular, wet-spot magmatism may include some kimberlites and late-orogenic alkali magmatism.

Internal vorticity and shear-sense indicators in tectonites

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A completely coaxial strain history in a deformed rock is extremely improbable. Therefore, in principle, a proper description of its strain history should include the internal vorticity components of that history. And geologists have often relied on 'shear-sense indicators' (SSIs) to constrain the vorticity of the deformation enjoyed by the rocks they examine.

But in fact, vorticity is very poorly constrained by SSIs. (1) We now commonly recognise that, in rocks with an initial 'active' anisotropy, SSIs can develop even if the strain history is strictly coaxial. (2) Conversely, an initially isotropic rock is likely to enjoy significantly large non-coaxial strain without its textural fabric recording any shear sense. (3) Except for progressive simple shear, there is no realistic natural or model 'machine' that can apply a large strain with vorticity components that are uniform in space and that remain constant in time.

In conclusion, SSIs cannot be used in any quantitative or even qualitative way to document a vorticity number for the deformation of a rock. SSIs record only what their name declares: a sense of shear along an active foliation or a lithotectonic contact. However important internal vorticity may seem to be, its history is, in practice, impossible to track.

SSIs are nevertheless important to record. (1) In some instances, a shear sense along a defined planar direction or contact may be all the geologist wants to know. (2) In many instances of highly deformed rocks, approximate progressive simple shear may be the dominant part of their deformation, its textural record overwhelming that of any other stage in the strain history. And that large, mainly progressive simple shear is often the part of the deformation history that interests the geologist.

Scaling of shear zones: A new local approach

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A new 2D method for scaling shear zones is presented. It involves calculating two parameters describing the strain heterogeneity in natural shear zones. The localization factor, Lf_{RA} , is the ratio of the shear zone area to a reference area, A_{RA} . A_{RA} is derived from foliation maps or images by Autocorrelation functions and satisfies geometric homogeneity on the scale of observation. Thus, it is a local feature depending on the foliation orientation distribution. Lf_{RA} can be understood as a normalized measure of shear zone area. The strain localization intensity, I_{loc} , quantifies the heterogeneity of transversal shear strain profiles. As a function of time, it yields insight on the strain hardening/softening behaviour of a shear zone system. It can be applied to Lf_{RA} as a weighting factor.

We determined Lf_{RA} for shear zones (Cap de Creus, NE Spain) formed at the frictional-viscous transition during a single deformational event over a broad range of scales. Plots of Lf_{RA} versus shear zone lengths show a set of data peaks that can be described by power-law distributions with exponent D . The characteristic length scales of these peaks coincide with length scales of compositional heterogeneities in the metapelitic and metapsammitic host rocks. D seems to systematically increase with scale. This is interpreted as an indicator of progressive shear zone weakening with scale. I_{loc} increases along and across the shear zones, also inferring shear zone weakening with strain and time.

Effects of a temperature drop during simple shearing in an analogue of polycrystalline quartz

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Microfabric evolution in quartz is modelled by deforming the analogue material norcamphor under plane-strain, simple-shear conditions. The equipment used for analogue modelling is a combination of a modified Means-Urai deformation rig and the Rotating Polarizer Stage. This setup allows us to monitor and record the microstructure and crystallographic orientations in the grain aggregate. The latter was previously possible only when the deformation was either interrupted or terminated. The main objective of our work is to study the sensitivity and stability of the microfabric due to a decrease in temperature during progressive deformation. We are reporting here on preliminary results in structural and fabric development. These are (1) strain localization in a high strain zone along the shear direction, and (2) the development of a fabric with a distinct bimodal grain-size distribution.

The Kaladar ‘metaconglomerate’: igneous or sedimentary protolith?

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The Kaladar metaconglomerate outcrops on Ontario Highway 41, approximately 3.5 km north of Highway 7. For at least 1 km, it borders the southern margin of the Northbrook ‘tonalite’. The ‘conglomerate’ has been metamorphosed under upper-greenschist to lower amphibolite facies conditions. Compositions of the stretched clasts are dominantly granitic and fine-grained mafic, rich in epidote and amphibole. Their long dimensions range in size from 5-30 cm. The axial ratios of the clasts range from 5:1 to 20:1. Walton *et al.* (1964) established the metamorphic grade by studying the compositionally zoned granitic clasts, and van de Kamp (1971) interpreted the matrix as being a mafic immature sandstone derived from the surrounding igneous rocks.

The northern contact of the ‘conglomerate’ with the Northbrook tonalite has been hydrothermally altered, with epidote and calc-silicate prevalent. Also, occurring throughout the ‘conglomerate’ are extensional filled fractures within the mafic clasts. At a recent ‘Friends of the Grenville’ (FOG) field trip, some participants suggested that the clasts, rather than being metasedimentary conglomerate clasts, could be less deformed remnants of Northbrook tonalite within an anastomosing and hydrothermally altered shear zone. The shearing would have allowed access to fluids resulting in the epidotic alteration of the sheared matrix and to a reduction in strength, leading to the isolation of relatively undeformed tonalite clasts within the sheared matrix. This project proposes to identify the protolith of the ‘conglomerate’ through detailed field mapping, geochemistry, and an investigation of principal strain directions in both the Northbrook tonalite and conglomerate. Preliminary geochemical results suggest that the matrix of the ‘conglomerate’ is very different from the tonalite, but that the ‘granitic’ clasts could be interpreted as silicified tonalite.

Ductile thrusting vs. channel flow in the southeastern Canadian Cordillera: a 3-D model for nascent channel flow in the infrastructure of a coherent crystalline thrust sheet

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The Late Cretaceous Gwillim Creek shear zone, exposed in the core of the Valhalla complex and located in the hinterland of the southern Canadian Rocky Mountain thrust belt, is a 5 – 7 km thick, easterly verging, ductile thrust zone. It was active after ca. 90 Ma and during anatexis (800°C and 800 MPa), rose eastward in the direction of transport, up a 12 km high ramp, and its base was refrigerated from below at ca. 60 Ma by thrust translation onto a cold footwall. Extensional shear zones are younger than the Gwillim Creek shear zone, and they do not significantly disrupt a plutonic edifice that bolts a Middle Jurassic suprastructure to a Late Cretaceous – Paleocene infrastructure. There is no evidence of channel flow or ductile extrusion. Instead, a 30 km thick, coherent sheet was translated on the Gwillim Creek shear zone, which at depth, was linked to the Foreland thrust and fold belt such as to form a composite crystalline thrust sheet. The infrastructure of that crystalline thrust sheet terminates at a subsurface "tip line" where ductile top-to-the-east "detachment flow" (Williams et al. in press) was transferred to ductile thrusts. North of the Valhalla complex, in the region of the Monashee complex, the infrastructure was thicker and hotter than it was to the north or south. In the corresponding foreland to its east, Late Cretaceous shortening was at a maximum, suggesting a foreland-hinterland link.

Channel flow, proposed by others in and/or near the Monashee complex, could have evolved within the infrastructure of the crystalline thrust sheet by activating an upper detachment and lateral transition zones such that the hotter, weaker channel material flowed ahead of its overlying suprastructure and its surrounding infrastructure. The channel would have been "tunneling," and its incremental forward flow would have introduced additional volume to the "tip line" region that would have to have been accommodated by a combination of structures in that region. These considerations suggest a 3-D model for a channel set within an infrastructure with a "tip line" (Figure 1). The channel has a thickness, T , between the lower and upper detachments, a length, L , in the dominant flow direction, and a width, W , between the lateral transition zones. The channel proposed for the Monashee complex region may have had a width of 250 - 300 km and a thickness of 10 - 20 km. Preservation of older structures within the channel, near its margins, as well as the absence of obvious flow balancing structures in the tip line region, suggest quenching at a nascent stage. If correct, this could present exciting research opportunities.

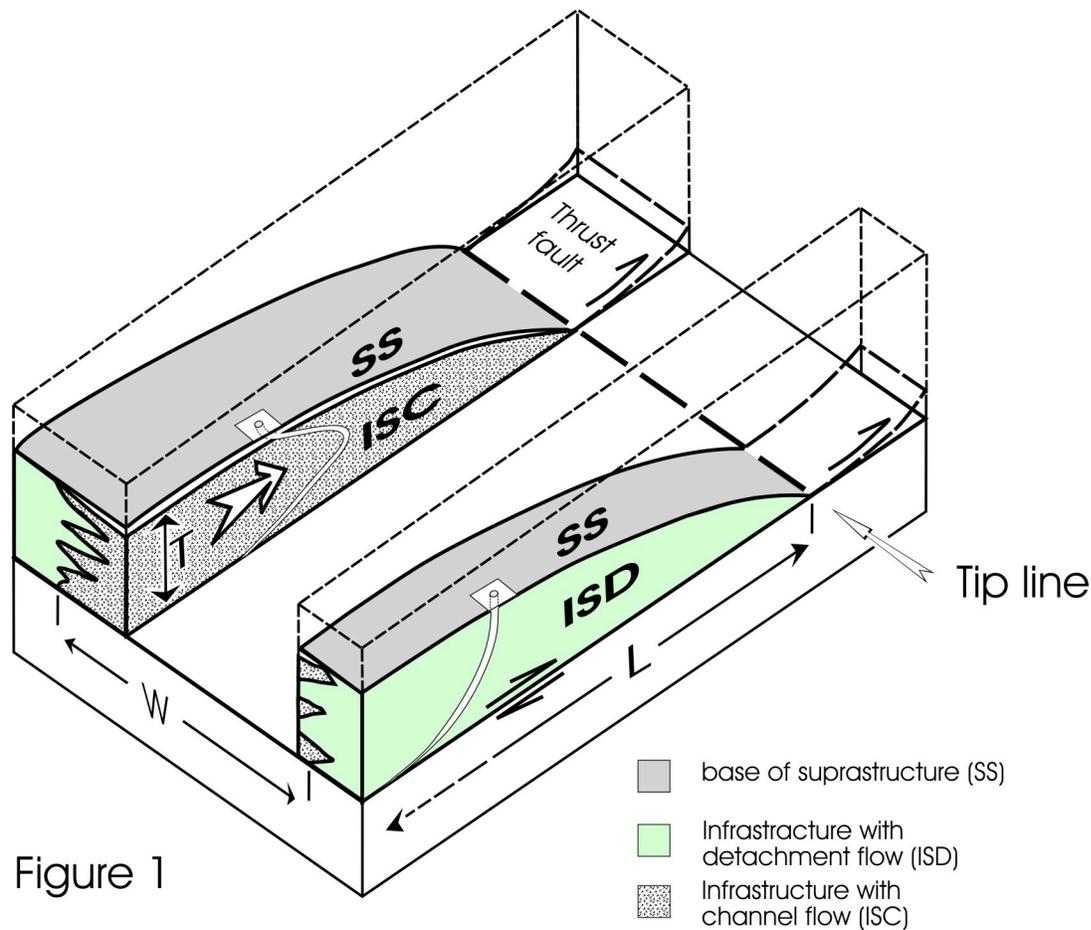


Figure 1

Figure 1. Block diagram, with central portion cut out, illustrates a channel, of width (W), thickness (T) and length (L), nested inside a flow zone with "detachment flow" outside the channel. The "tip line" schematically represents the zone of transition from flow in the hinterland to ductile thrusting in the internal portion of a thrust belt. SS = suprastructure. The zigzag line, on the left face of the block, schematically represents the lateral transition from channel flow (ISC) to detachment flow (ISD). Two failed tectonic rock bolts illustrate the difference in flow inside and outside the channel.

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How to do structural geology on Mars with Orion software

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Structural studies on Mars have largely been limited to the visual interpretation of structures from orbiter images. The recent availability of good elevation measurements on Mars, along with the large scale of the features found there, has made it possible to study the three-dimensional geometry of that planet's surface structures using a modified three-point method. The development of Orion software has made applying that method particularly easy. Originally devised to analyze terrestrial satellite images, Orion has been enhanced to handle the data formats used for planetary studies.

Orion's raw data are orthorectified satellite images, combined with a digital elevation model (DEM), a grid of elevation values covering the region of the image. The user identifies a lithological or structural contact in the image and selects a series of sample points along that contact assumed to lie on an approximately planar surface. Orion uses the 3-dimensional spatial coordinates of these points to compute the best-fit planar surface through them using multilinear regression, displaying the fitting statistics. Tools are available to adjust the choice of points and their position. Orion updates the best-fit calculation as new points are added or existing points are moved or deleted. At any time, the user can check the quality of the fit by observing the trace of the fitted plane projected on the image surface. Once the user is satisfied with the fit, the points and calculations are stored and the computed plane appears on the image as a structural symbol. The symbol can be either the standard strike/dip symbol or our newly devised dip/dip-azimuth symbol that includes the computed errors. Then, a new contact can be sampled. In this way, a large number of structural measurements can be made fairly quickly, producing a structural map of the image area.

Orion includes a number of additional features that help users analyze and present the results:

- a stereonet, with full statistical contouring and principal direction analysis
- a rotatable 3-dimensional block diagram, which may include the currently fitted plane
- a topographic cross section, including all projected planes intersecting the chosen traverse line
- an red-blue anaglyph of the satellite image showing the 3-dimensional surface for visualizing the topography
- a map layer with a wide range of structural symbols to annotate the image for presentation

Orion provides all graphs and calculation results as printed output and as publication-quality graphic image files or text file listings.

Discrimination of Archean Domains in the “Sachigo Subprovince”, Northwestern Ontario

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The large region of Archean crust north of the Uchi Subprovince in northwestern Ontario has commonly been called the Sachigo Subprovince. Recent work through LITHOPROBE and Natmap studies has encouraged further subdivision of this region into tectonic domains and terranes (*senus lato*). Previous work by other workers near the Ontario-Manitoba border has tentatively subdivided the far northern part of the Sachigo Subprovince into several terranes, using U-Pb zircon dating and Sm-Nd isotopic analyses. The current study was designed to complement this work by focussing on a reconnaissance transect across the eastern Sachigo to determine the eastern boundaries between the proposed terranes. We obtained samples from exposed outcrops of tonalite gneiss and granodiorite, northeast of Kasabonika Lake, a dacitic volcanic sample from the McFaulds VMS discovery on the western edge of the James Bay Lowlands, and from drill core within the James Bay (JBL) and Hudson Bay lowlands (HBL). These were analyzed with the GSC's SHRIMP facility for U-Pb zircon and the multi-collector ICP-MS for Sm/Nd tracer isotopic analyses.

The results demonstrate that the Neoproterozoic Oxford-Stull terrane (OST), the greenstone belts of which are composed largely of basalts of oceanic affinity, continues and expands eastwards under the James Bay Lowlands. This terrane appears to be characterized by a predominance of Neoproterozoic magmatic ages, ranging generally from 2690 Ma to 2740 Ma, and by $\epsilon\text{Nd} > 0$, which confirms that this terrane is relatively juvenile. This is consistent with results obtained by Skulski et al. (2000) that defined the northern and southern limits of the OST across the Ontario-Manitoba border. The northern boundary of this terrane appears to be defined by the North Kenyon fault, which can be traced from Manitoba across Ontario close to the edge of the HBL. This fault marks the southern limit of the Northern Superior superterrane (NSS), which underlies the HBL and is characterized by the presence of Mesoproterozoic to Paleoproterozoic inherited zircons within plutonic bodies and by $\epsilon\text{Nd} < 0$, confirming significant older continental crustal influence.

The southern limit of the OST in eastern Sachigo Subprovince is more debatable although ϵNd evidence and the presence of Mesoproterozoic inherited zircons from a drill site along strike and east of the Wunnummin Lake greenstone belt (WLB) strongly support other lines of geological and geophysical evidence that the WLB marks a major tectonic boundary between the OST and the dominantly Mesoproterozoic North Caribou superterrane to the south.

Within the NSS, from a drill site that sampled an Archean granitic dike under the HBL, there is evidence of old Mesoproterozoic crustal influence from $\epsilon\text{Nd} = -1.69$ and Nd model age (DePaolo 1981, depleted mantle model) of 3.10 Ga. The evidence under the Hudson Bay Lowlands is consistent with results obtained farther west by Skulski et al (2000) in exposed Archean rocks along the southern edge of the HBL and north of the North Kenyon fault. However, the NSS in Ontario contains widespread evidence of Neoproterozoic magmatism (e.g. Stone 2005) in addition to evidence of much older inherited zircon sources. In addition, we find that quartz arenite beds, lying unconformably upon the Archean basement at two widely separated sites in the JBL and HBL, contain strikingly similar Neoproterozoic populations of detrital zircons ranging respectively from 2664 to 2770 Ma and 2668 and 2745 Ma. The NSS clearly has had a long and complex history.

The geochronological and isotopic record thus far supports the conclusion that two older Archean superterranes containing widespread evidence of continental influence are separated by a younger Neoproterozoic terrane of largely juvenile affinity that extends belt-like from Manitoba across Ontario to the James Bay Lowlands.

Precambrian geology of the Muskoka Lakes Region, Central Gneiss Belt, southwestern Grenville Province

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A geological map, at the scale of 1:100,000, has been assembled for the Muskoka Lakes region to show the regional distribution and relationships of the rock types encountered on the CTG field trip. The map is a compilation of six map sheets from a series of 1:50,000 map sheets published by the Ontario Geological Survey, a series which covers the southwestern portion of the Central Gneiss Belt in the Grenville Province. Although not outlined on the assembled map, its area includes a number of the domains and subdomains shown in Figure 2 of the field guide. The geologic information represented on the six map sheets is the result of a long-term research project carried out by S.B. Lumbers and V.M. Vertolli, who worked in the Muskoka Lakes region from 1979 to 1996. Associated laboratory work included the examination of about 1200 thin sections, over 650 modal analyses, 225 whole-rock and trace-element chemical analyses, and numerous REE analyses to help determine the origin of the rocks.

Channel flow in the Paleoproterozoic– can we see beneath Tibet?

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Topographically driven ductile flow in the lower crust as a consequence of continent-continent collision has been linked both to the development of mid- to lower crustal low-viscosity deformation channels and the thinning of tectonically overthickened crust through extrusion both parallel and oblique to the primary orogen convergence direction. The paradigm for such behaviour is the Himalaya-Tibetan system in which the actively convergent Indian-Eurasian plates provide a range of geological and geophysical data. Although the leading edge of the Himalayan convergence has exhumed some mid-crustal material, the bulk of lower crust lies beneath Tibet, such that the behaviour on which prescribed models depend remains accessible only by remote geophysical methods. These crustal levels can be directly observed only in deeply eroded orogens such as occur in Precambrian terrains.

Collision between the Archean Superior and Rae cratons in the Ungava - Baffin Island transect of the Paleoproterozoic Trans-Hudson orogen has generated a remarkably continuous lower crustal section. The latter extends from foreland basin units on the lower plate (Superior) through plutonic and supercrustal units in the core of the orogen to sedimentary cover and basement of the upper plate (Rae). Late folding has exposed the Superior craton-Proterozoic contact, allowing study of along-dip variation in kinematics. This primary protolith boundary has distinct mechanical responses and kinematic records at different paleodepths. Within the foreland of the Superior craton, imbricated Proterozoic basinal units exhibit simple stretching lineation fabrics parallel to the tectonic transport direction and the tectonic contact (25 km paleodepth) with the craton is a 0.5-3m thick mylonitized zone. With increasing depth of deformation (but at currently higher structural levels), the stretching lineation patterns pass through a transition from sole orogen-perpendicular to orogen-perpendicular and orogen-parallel to sole orogen-parallel (50 km paleodepth). Likewise, the degree of cratonic lower plate involvement in Paleoproterozoic deformation increases, and exceeds 10 km on southern Baffin Island. At the latter level, a 15–20 km thick zone of distinct deformation corresponds to a kinematically defined ‘flow channel’ within which an inverted temperature gradient exists. Both within and adjacent to the ‘channel flow’, lineation and foliation development is consistent with a constant tectonic transport (shear) direction combined with a component of vertical shortening. The kinematic movement picture is equivalent to a subhorizontally orientated transpression zone with a relatively low ratio of simple shear strain/versus pure shear strain rate. As such, this crustal section is proposed as analogous to the ‘topographic’ ooze inferred to accommodate extension beneath the Tibetan plateau, and would predict a similarly thickened crust beneath the upper plate Rae craton during orogenesis. In a complementary fashion, the kinematics and fabrics observed in the Paleoproterozoic provide direct evidence for the type of behaviour expected beneath Tibet.

Why transposition by folding is incompatible with coeval thrusting

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Areas of flat lying foliation are ubiquitous in high-grade rocks, and they commonly comprise the infrastructure, of the infrastructure – superstructure association. They are generally characterised by transposition by folding, and the fabric is commonly interpreted as a product of internal thrusting. There are however, problems with this interpretation, two of which are discussed with special reference to the Monashee complex of the Canadian Cordillera.

Well documented thrusts occur in sedimentary rocks where there is a strong planar anisotropy. They ramp through layers, with reverse fault geometry, and follow the planar anisotropy for much of their length. It seems that the anisotropy is of prime importance in determining their geometry. In this situation there is little or no layer-parallel shear within the thrust sheets.

In areas of transposition by folding, fabrics indicate that shear approximately parallel to the foliation is penetrative. Common evidence comprises: (1) dragfolds at all scales with overlapping domains of influence, (2) penetrative S – C – C' fabrics, and (3) rotated porphyroblasts, boudins etc.. Since dragfolds are a common feature of the fabric it follows that there is no significant thinning of the infrastructure zone. It is also unlikely that there is significant thickening since the shear is so large that even doubling the thickness of the zone would not significantly lower the kinematic vorticity number. From experimental work, as well as field observations, we know that in situations where the simple-shear component is large compared to the pure-shear component, only one cross cutting feature generally forms and that is a C' shear band. No other plane is needed, since S and C' comprise two slip systems that are adequate to accommodate the plane strain of the zone as a whole, or the strain of a dyke for example, that is rotating towards parallelism with the zone. The C' plane has the opposite dip to that of a potential thrust ramp associated with the same flow.

This argument is supported by observations in the Thor Odin culmination of the Monashee complex. Flow is top-to-the NE and related shear bands, cut offs, and oblique boudin terminations, all dip to the NE. Slip does occur on the transposition foliation (S_T), or in narrow layers parallel to S_T , but it is restricted to the foliation plane, or joins up with C', so that their combined geometry and kinematics is that of a normal fault, with respect to the sense of shear.

Another problem is that there is evidence that infrastructure zones inherit upright folds which become modified by horizontal flow into recumbent folds. This is not a situation that would encourage the development of thrusts. As transposition proceeds, the foliation becomes more conducive to thrusting, but is continually being modified by dragfolding at all scales, so that it is still not conducive to thrusting. Where faults or shears zones do develop parallel to S_T they are C or Y shears. This is not just semantics, because there is no reason why they should place old stratigraphy on new, a characteristic of thrusts, nor can they be treated as thrusts for restoring section. Finally, if they are through-going structures they must be late or they would be folded like all other markers.
